Loss of High Frequency Upon Propagation Through Shock-Damaged Rock

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ABSTRACT: The attenuation of stress waves in samples of gabbroic rock subjected to shock loading up to 11 GPa is studied. We determine the attenuation coefficients, α_p, for samples with different damage parameters under dynamic strains of $2x10^{-7}$ and at frequencies around 2 MHz using the ultrasonic pulse-echo method. A fit to the data yields the P-wave spatial attenuation coefficient versus damage parameter: $\alpha_p = 40.9\ D_p - 30.5\ D_p^2$ (db/cm). Basing on O'Connell-Budiansky theory a relation between attenuation coefficient and crack density is derived. The predictions of α_p and Q from Walsh's theory agrees well with the experiment results for the samples with different damage deficits and the Q's we measure are in the range of 10 to 20. These very low values give rise to the sharp decrease in high frequency seismic energy, as the stress-wave from an explosion leaves the source region.

Key Words:

attenuation
shock-damage

OBJECTIVE:

The attenuation of stress waves in rocks is largely caused by internal friction between crack surfaces. When a stress-wave propagates in rock this induces differential motion along the usually present cracks [Born, 1941; Walsh, 1966]. Generally, attenuation depends on stress amplitude and frequency, as well as, pressure, temperature and fluid saturation.

Experimental measurements of attenuation of stress waves in several rocks have been extensively studied since the 1940's in the laboratory using different techniques over a wide-frequency range [Born, 1941; Toksoz et al., 1979; Winkler and Plona, 1982]. All these studies concentrated on the relations between attenuation and parameters other than crack density induced velocity deficits. Because attenuation is directly related to crack density, research on influence of crack density on attenuation can provide detailed information about the mechanism of attenuation. The present study presents the first experimental data of the P-wave attenuation of gabbroic rocks (San Marcos, CA) which are pre-damaged by shock waves.

EXPERIMENTAL TECHNIQUE:

Sample Preparation

The rock studied was San Marcos gabbro which has been studied previously [Ahrens and Rubin, 1993; Rubin and Ahrens, 1991] The density of San Marcos gabbro is 2.87 g/cm^3, and there is very low initial crack density.

Initially a large gabbro target with dimensions 200x200x150 mm was impacted by a lead projectile at a velocity of 1.2 km/s, the projectile had a diameter of 7 mm and mass of 3 gm. The pressure of the shock wave in the target was estimated to be about 11 GPa at a radius of 0.35 cm and about 0.1 GPa at radius of 8 cm from the impact site along the center-line of the impact using a power-decay relation and impedance match method [Ahrens, 1987; Ahrens and Johnson, 1995].

The recovered target was cut into 1 cm cubes with two surfaces being perpendicular to the impact axis. The 1 cm cubes were polished to $\pm$ 0.03 mm. Prior to measurement, the samples were dried in an oven under normal pressure at 100° C for 24 hours.

Damage Parameter for P-wave

For the damage parameter, we follow the definition used in Grady et al. [1987] and Ahrens et al. [1995] which gives

$$D_p = 1 - \left(\frac{C_p}{C_{p0}}\right)^2 \quad (1)$$

where D_p is the damage parameter for a P-wave, C_p is the P-wave velocity measured for the damaged samples and C_{p0} is the intrinsic P-wave velocity for initial samples.

Attenuation Coefficient

The ultrasonic experimental apparatus used in this work is similar to that developed by Winkler et al. [1982] for attenuation coefficient measurements (Fig. (1)).

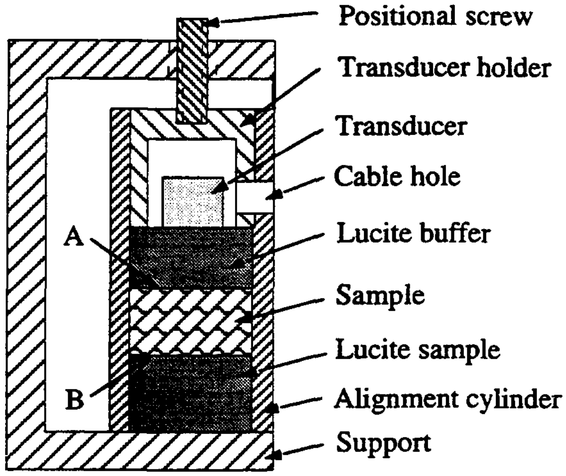

Fig. 1 Measurement system

Suppose that the reflecting and transmission coefficients of the surfaces between the buffer and sample are equal to that for plane-wave incidence as in Winkler et al. [1982], the changing amplitude of the wave is then totally from intrinsic attenuation. Let R be reflection coefficient for the interface between the coupling buffer and sample and L/2 be sample thickness, A(f) and B(f) be the frequency-dependent amplitudes of the pulses reflected from the surface A and B (in Fig. 1) of the sample, respectively. The attenuation coefficient obtained from the two reflected stress waves is expressed as [Winkler and Plona, 1982]

$$\alpha(f) = \frac{8.686}{L} \ln\left[\frac{A(f)}{B(f)}\left(1 - R^2\right)\right] \tag{2}$$

where the unit of $\alpha(f)$ is db/cm when the unit of L is cm and R is expressed as

$$R = \frac{C_p\rho - C_{pc}\rho_c}{C_p\rho + C_{pc}\rho_c} \tag{3}$$

where C_p and ρ are the P-wave velocity and the density of the gabbro sample measured, respectively. C_{pc} and ρ_c are the P-wave velocity and density of the coupling buffer (Lucite). From ultrasonic measurements, C_{pc} is 2.68 km/s and ρ_c is 1.19 g/cm^3.

A piezoelectric transducer (Panametrics, Model 102) is used as the pulse generator and the receiver. The transducer's driver is a Panametrics 505UA pulser/receiver. The recorded signals are used to calculate the magnitude of each frequency component of each pulse using a Fast Fourier Transformation (FFT).

PRELIMINARY RESEARCH RESULTS AND ANALYSIS:

A typical signal recorded for the attenuation measurement is shown in Fig. 2, in which the first signal is reflected from the surface A of the sample and the second from the surface B, and T_1 and T_2 are the data length used in FFT. We also measured the strain in the rock produced by the ultrasonic transducer. The strain level is 10^{-7} and, the present data are taken in the ultrasonic region, the results are also applicable to seismic frequencies.

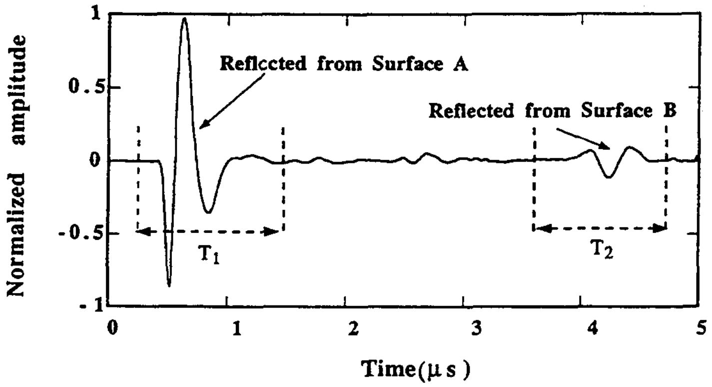

Fig. 2 Typical ultrasonic record

A typical result of spectral analysis is shown in Fig. 3, it is found that most of energy of the stress wave generated by the transducer is concentrated in the frequency range between 1.5 and 3.5 MHz. Using Eq. (2), the attenuation coefficients for the samples with differential damage parameters have been evaluated as shown in Figs. (4) (5) and (6). From Fig. (4), we can see that the attenuation coefficients for samples with different damage parameters increase approximately linearly with frequency. From Fig. (5), the relation between attenuation coefficient and damage parameters for 2 MHz are fitted as

$$\alpha_p(\mathrm{db/cm}) = 40.9D_p - 30.5D_p^2 \tag{4}$$

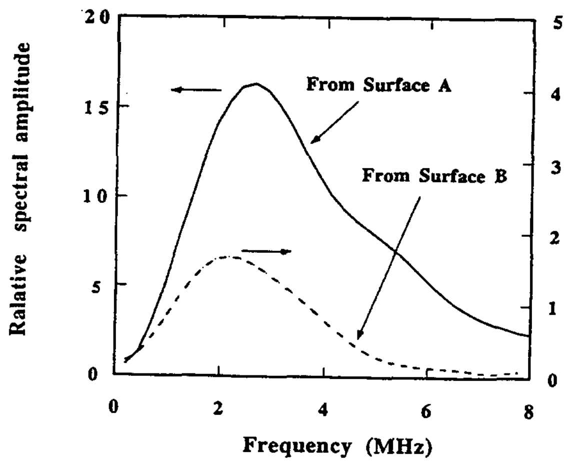

Fig. 3 Typical spectral amplitude of signals

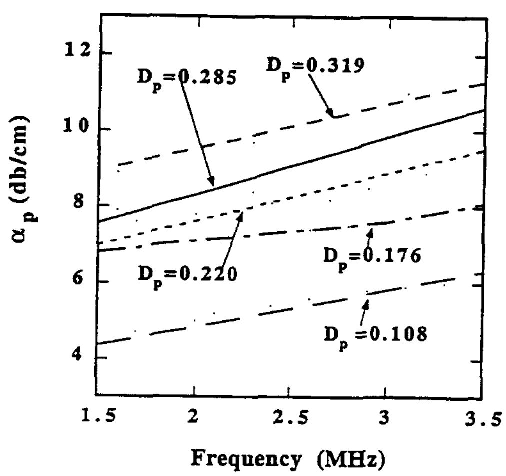

Fig. 4 Experiment results of attenuation coefficient with frequency for samples with different damage parameters

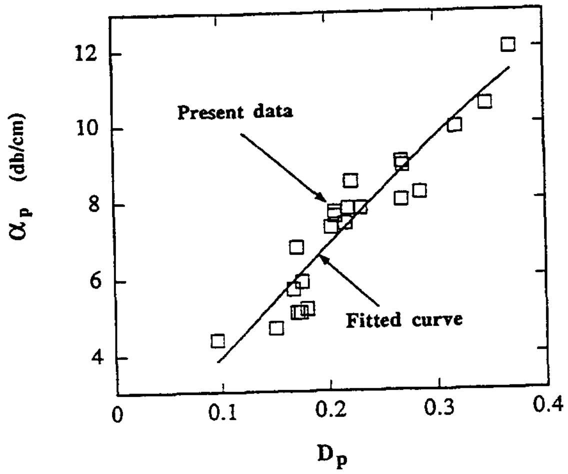

Fig. 5 Relation between damage deficits and attenuation coefficient

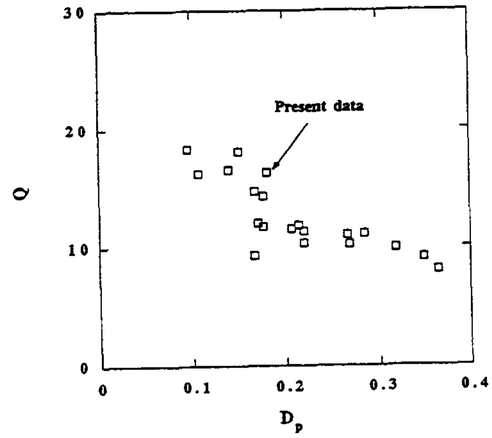

Fig. 6 Quality factor versus damage deficits

O'Connell and Budiansky [1974] established the relation between velocity and crack density follows as

$$\left(\frac{C_p}{C_{p0}}\right)^2 = \frac{(1-\nu)(1+\nu_0)}{(1+\nu)(1-\nu_0)}\left(1-\frac{16(1-\nu^2)\varepsilon}{9(1-2\nu)}\right) \tag{5}$$

$$\frac{\nu}{\nu_0} = 1 - \frac{16\varepsilon}{9} \tag{6}$$

where ν and ν_0 are effective and intrinsic Poisson's ratio, respectively. ε is crack density which is defined as

$$\varepsilon \equiv N < a^3 > \tag{7}$$

where N is the number of cracks per unit volume and a is the half-length of cracks.

From the definition of damage parameter, Eq. (1), and the relation between velocity and crack density, Eqs. (5), (6) and (7), the relation between D_p and ε is approximately

$$D_p = 2.4\varepsilon - 1.2\varepsilon^2 \tag{8}$$

From Eqs. (4) and (8), an approximate expression relating α_p to ε is

$$\alpha_p = 96.1\varepsilon\left(1 - 2.2\varepsilon + 1.69\varepsilon^2 - 0.4\varepsilon^3\right) \tag{9}$$

Figure 7 presents experimental results of attenuation versus crack density and the fitted curve. It can seem that increasing rate of attenuation coefficient versus crack density decreases with crack density. This can be explained using the relations among attenuation coefficient, crack density and half-length. From the definitions of the attenuation coefficient and crack density, the attenuation coefficient is related to the area of crack surface, this means $\alpha_p \propto a^2$, therefore, from the definition of crack density, we have

$$\frac{\alpha_p}{\varepsilon} = \frac{b}{a} \tag{10}$$

where b is a constant. Therefore, the ratio, $\frac{\alpha_p}{\varepsilon}$, must decrease with increasing of crack density. This is shown by the experimental results of Fig. 7. Moreover, in Fig. 6 we suppose b is a constant, the average half-length of cracks can be estimated as shown in Fig. 8.

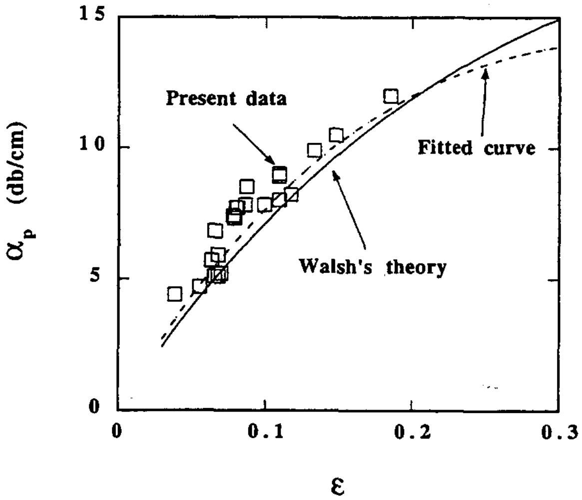

Fig. 7 Relation between attenuation coefficient and crack density

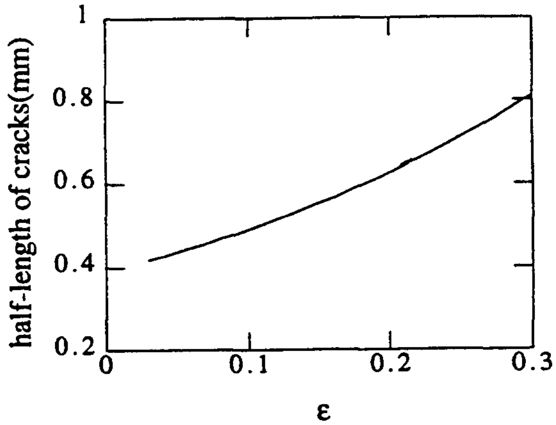

Fig. 8 Estimated average half-length of cracks versus crack density parameter

Basing on the concept that frictional dissipation at crack surfaces in-contact slide relative to one another during the passing of stress wave, Walsh [1966] developed an expression for the attenuation coefficient that can approximately be expressed as

$$\alpha_p = Hf\varepsilon \frac{K(1-\nu)(1-2\nu)}{K_0(1-2\nu)(1-2\nu_0)} \tag{11}$$

where H is considered to be a constant and f is frequency. Only one parameter, H, needs to be determined. If let $\varepsilon = 0.1$, from Eqs. (6), (8), the relation between K and K_0 [O'Connell and Budiansky, 1974] and experimental results of attenuation coefficient, H is evaluated to be 60.7db/cm for f = 2 MHz.

The calculated results from Eq. (11) is shown in Fig. 7. It is obvious that the form of Walsh's theory is in good agreement with the experimental results and the relation between α_p and ε is not linear. This result demonstrates that Walsh's theory can be used to evaluate attenuation coefficient in rocks with high crack densities such as occur in the very close vicinity of contained explosions.

CONCLUSIONS AND RECOMMENDATIONS:

Some 20 samples of San Marcos gabbro cut from a shock loaded target are used to measure attenuation coefficients for different damage levels experimentally using the ultrasonic method. We used O'Connell and Budiansky's theory for relating crack density to elastic constant with various damage parameters. Walsh's theory [1966] was used to predict the attenuation coefficients of the samples with different crack density. Our main conclusions are:

(1) The P-wave attenuation coefficient and the damage parameters are given by Eq. (4).

(2) Based on the O'Connell and Budiansky's theory, the relation between the crack density and attenuation coefficient can be expressed approximately as Eq. (9).

(3) Basing on Walsh's theory, we evaluated the attenuation coefficient. The predictions of attenuation coefficient fit experimental results as shown in Fig. (7). Moreover, the Q's of damaged rocks are low, 10-20. This gives rise to the very strong attenuation of the high frequency portions of the seismic signals from contained explosions.

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